Simulation of HEAO 3 Background

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Abstract- A Monte Carlo technique for modeling background in space-based gamma-ray telescopes has been developed. The major background components included in this modeling technique are the diffuse cosmic gamma-ray flux, the Earth's atmospheric flux, the decay of nuclei produced by spallation of cosmic rays, trapped protons and their secondaries, the decay of nuclei produced by neutron capture, and the de-excitation of excited states produced by inelastic scattering of neutrons. The method for calculating the nuclear activation and decay component of the background combines the low Earth orbit proton and neutron spectra, the spallation cross sections from Alice91, nuclear decay data from the National Nuclear Data Center's (NNDC) Evaluated Nuclear Structure Data File (ENSDF) database, and three-dimensional gamma-ray and beta transport with Electron Gamma-ray Shower version 4 (EGS4). This Monte Carlo code handles the following decay types: electron capture, β^- β^+, meta-stable isotopes and short lived intermediate states, and isotopes that have branchings to both β^- and β^+. Actual background from the HEAO 3 space instrument is used to validate the code.

I. Introduction

Calculations of the radioactive background in gamma-ray detectors has been a challenging problem since before the first balloon flight of a gamma-ray detector [1]. Reliable calculation of the background rate is essential for future missions because the sensitivity of a gamma-ray telescope is background limited. A Monte Carlo simulation code has been developed that models the background rate due to the decay of spallation products in space based gamma-ray telescopes [2]. The measured background for the High Resolution Gamma-ray Ray Spectrometer aboard High Energy Astrophysics Observatory (HEAO 3) was used to validate this code. This model includes the geometry and composition of the instrument, the incident proton and neutron fluxes on the components of the detectors, the cross-sections for spallation, inelastic scattering, and neutron capture. This model also includes the branching ratios in the decay scheme for the unstable spallation products, and the half-lives of the unstable spallation products, and the Monte Carlo transport code that propagates gamma-rays and beta particles. The Monte Carlo code does not model alpha decays or propagate alpha particles, protons, and neutrons.

II. Model

A mass model describing the geometry and materials was made for the components of HEAO 3. HEAO 3 consisted of four Ge co-axial detectors in a CsI anti-coincidence shield. Each of the Ge detectors was 5.4 cm in diameter and 4.5 cm thick. The detectors were held in a thin aluminum cup. These were all contained in an aluminum cryostat. There was an aluminum cold plate between the detectors and a silver cold finger. There also was a stainless steel baseplate (nominally composed of 10% nickel, 20% chromium and 70% iron). The cryostat was surrounded on all sides by a 6.6 cm thick CsI shield, with holes in the upper lid of the shield collimating the field of view to ~30^o [3]. The decays of isotopes produced by the neutron and proton activation from components of the instrument that were made of Ge, Al, CsI, steel and Ag were modeled. Components of the spacecraft outside the shield were not included in this work.

The activation of the detectors and surrounding materials was due to a flux mostly composed of secondary neutrons and protons produced by cosmic rays and trapped protons incident on the spacecraft. HEAO 3 was in an orbit with 500 km altitude with an inclination of 44^o [3]. In this work, the proton and neutron flux inside the shield was estimated according to the scaling method used by Gehrels [4]. This method was based on data from the balloon instrument, Low Energy Gamma-ray Spectrometer (LEGS), and scaled to predict fluxes as a function of altitude and orbit inclination [5].

III. Simulation

The cross-sections for spallation from neutrons and protons incident on the detectors, shields and support structures were taken from Alice91 [6]. These cross-sections and the neutron and proton flux were evaluated over the

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energy range of 2 to 250 MeV, thus primary cosmic-ray protons (> few GeV) are not included in this model. The reported errors on the Alice91 spallation cross-sections were less than 30%. The NNDC's Evaluated Nuclear Data File (ENDF) database contains measured cross-sections for neutron capture and inelastic scattering of neutrons to excited states. The model used the gamma-ray spectrum from the Earth's atmosphere as measured by the Solar Maximum Mission (SMM) [7]. This spectrum was folded through both the open collimator response and the response to shield leakage. A ^{40}K calibration source was modeled inside the cryostat and was fitted to the measured data only at the 1.46 MeV line. The cosmic diffuse gamma-ray background was from the HEAO 1 A4 experiment [8]. This flux is also folded through the open collimator response and the response to shield leakage. The ENSDF database was used for beta branching ratios, half-lives, energy levels and gamma-ray branching ratios for decay products, as well as the half-lives of intermediate states of decay products (>1μs). Also included in NNDC databases were the x-ray fluorescence yields and energies of the characteristic x-ray(s) for each isotope [9].

EGS4 is a Monte Carlo transport code that was used for beta and gamma-ray transport [10]. Included in EGS4 are routines for photon interactions (photoelectric absorption, Compton scattering, and pair production), as well as routines for the scattering of electrons (ionization energy losses, Möller, Mott and Bhabha scattering). The combinatorial geometry package MORSE-CG was used for three-dimensional propagation of beta particles and gamma-rays.

A routine was designed and implemented for initializing EGS4 to model a nuclear decay, one decay at a time. The beta particle and gamma-rays for a given isotope in a single decay are produced from a single series of branchings in a cascade to the ground state of the decay product. This cascade is produced starting from the beta-unstable spallation product isotope and ends at the ground state of the decay product. At the beta-unstable spallation product a beta endpoint energy or Electron Capture (EC) energy or Internal Transition (IT) is chosen via Monte Carlo. If a beta branch was selected, the endpoint energy for that branch was used to determine the energy of the beta particle from the appropriate beta-spectrum distribution [12,13]. The beta endpoint energy, or the EC energy, was subtracted from the ΔQ value for the decay of this beta unstable spallation product to determine the energy level of the decay product for the start of the gamma-ray cascade. At each energy level of the decay product a gamma-ray was randomly selected from the possible gamma-rays for that energy level according to their branching ratios. The next energy level was determined by subtracting the energy of the gamma-ray selected from the value of the previous energy level until the ground state of the decay product is reached. This routine can distinguish between unstable isotopes that decay by only β^+, only β^-, only EC, only IT, and isotopes that decay by different ratios of any combination of β^+, β^-, EC, and IT. After each cascade to the ground state the inclusion of a K or L shell x-ray is determined from the fluorescence yield of the decay product by Monte Carlo.

Multiple decays were modeled for each beta-unstable isotope. For every decay the energy deposited by each interaction in the detectors or the shield was summed for each detector and the shield. The energy resolution was applied to the summed energy for each active element. Then

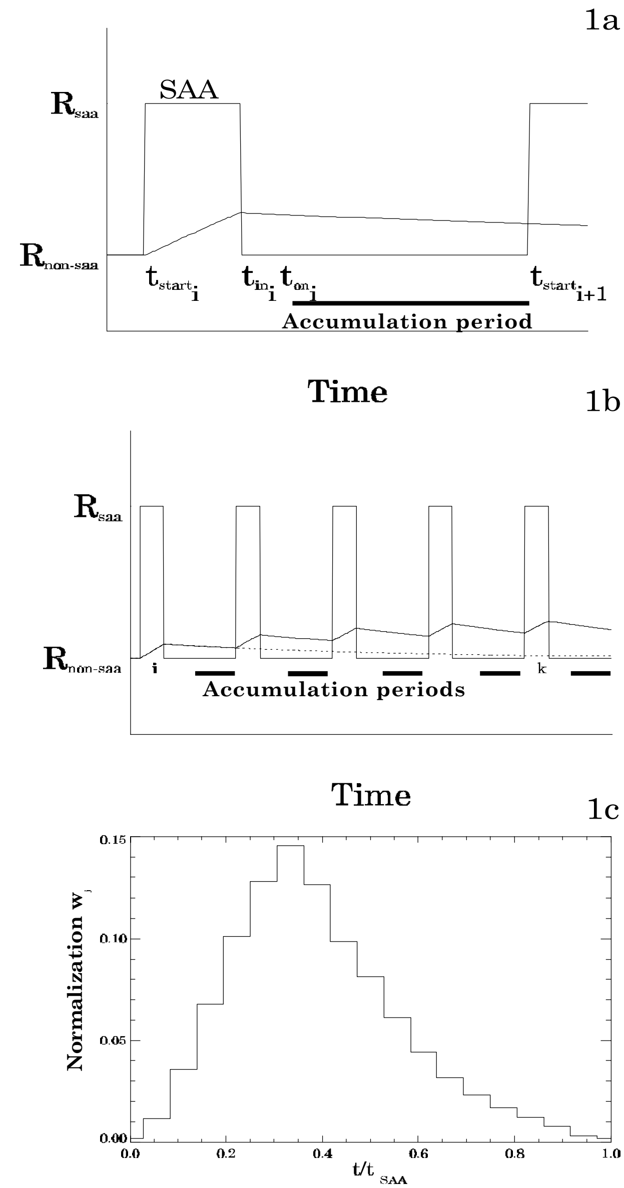

Figure 1 (a) Production and decay rates for an unstable isotope during a single SAA passage. (b) Production and decay rates accumulated over several SAA passages and orbits. (c) The normalization of the particle fluxes during SAA passage [11].

a histogram was made of all decays of a spallation product where the energy deposited in the detector was above the detector threshold, and the energy deposited in the shield was below the shield's threshold. These histograms were summed together with appropriate normalization for the decay rate of each isotope and summed with the cosmic diffuse gamma-ray flux, the Earth's atmospheric gamma-ray flux, and signals from the elastic scattering of neutrons. The total spectrum was compared to the measured background rate.

The production rate for each beta-unstable isotope j is

$$R_{prod_j} = \sum_i \int f_n(E) \quad {}_{n(i,j)}(E) a_i \quad {}_i \frac{N_o}{A_i} V dE + \sum_i \int f_p(E) \quad {}_{p(i,j)}(E) a_i \quad {}_i \frac{N_o}{A_i} V dE\,, \tag{0}$$

where i is a stable isotope in volume V, a_i is its fractional abundance, $_i$ the density, N_o is Avogadro's number, A_i is the atomic weight, $_{n(j,i)}$ and $_{p(j,i)}$ are the cross-sections for neutron and proton spallation to beta-unstable isotope j from isotope i, and f_p and f_n are the proton and neutron fluxes [5]. The fractional abundance a_i was calculated for the isotopic fraction for each element in each material.

Accounting for the variable decay rate for each unstable isotope is important for space-based gamma-ray telescopes that pass through the South Atlantic Anomaly (SAA). Production of unstable isotopes made during passage through the SAA contribute to the background during the accumulation intervals between SAA passages (Figure 1a). For HEAO 3, a daily SAA exposure was typically 220 minutes per day. Ten SAA passages per day were modeled. Data was collected by HEAO 3 starting 600 s after an SAA passage until the beginning of the next SAA passage.

The additional production of unstable isotopes during passage through the SAA is $D_R = R_{saa} - R_{non-saa}$, where R_{saa} is the rate of production during passage throught the SAA, and $R_{non-saa}$ is the rate of production outside the SAA passage. Both are calculated using Equation (1). For each isotope the total decay rate is

$$R_{decay} = R_{prod_{non-saa}}(1 - e^{- \ t}) + \frac{\sum_{i=0}^{t_i \le t} \sum_{k=i}^{t_k \le t} \sum_{j=0}^{q} w_j D_R T_{saa} \left(e^{- \ (t_{on(k)} - t_{in(i)})} - e^{- \ (t_{start(k+1)} - t_{in(i)})}\right)}{\sum_{i=0}^{t_i \le t} (t_{start(i)} - t_{in(i)})}, \tag{2}$$

where t is the time since launch, and t_{start} is the start time of an SAA passage, is the time constant, t_{in} is the end of an SAA passage, t_{on} is the time the detectors are turned on after an SAA passage is over as shown in Figure 1a, i is an index over all SAA passages, k is an index over all periods between SAA passages following the i^{th} SAA passage for up to an arbitrary cut-off, and w_j are the relative rates within q SAA time bins, as shown in Figure 1c. Figure 1b shows the accumulating effects of successive SAA passages.

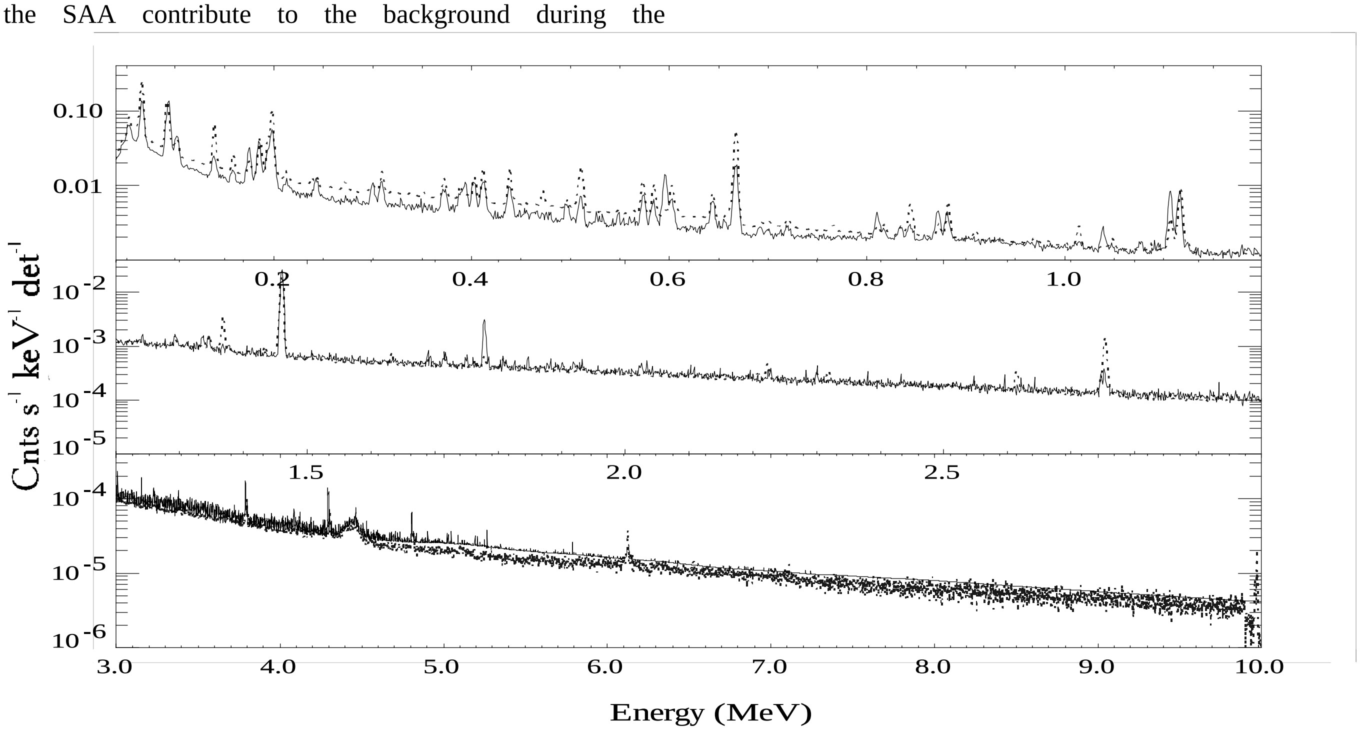

Figure 2. The sum of all components included in this model (solid curve) versus the measured background rate from HEAO 3 (dotted curve) [14]

Figure 2 shows the background spectrum modeled for HEAO 3 summed over all components and compared to the measured data taken from the first 50 days of operation [14]. Included in the model were all unstable isotopes with production >0.01% of the most abundantly produced isotope by spallation from Ge (56 isotopes), all unstable isotopes with production >1.0% of the most abundantly produced isotope by spallation from Al (11 isotopes), steel (33 isotopes), CsI (36 isotopes), and Ag (19 isotopes).

IV. Discussion

The Monte Carlo model for HEAO 3 captures most of the major line features and shape of the continuum background. Agreement is good throughout the background spectrum suggesting that the essential physics is being modeled correctly. In the continuum, the data and model agree to within 45% of each other. The difference can be partially attributed to the errors of ~30% in the spallation cross-sections in Alice91 and to the uncertainties in the proton and neutron flux. There are 133 lines observed in the data from HEAO 3. Forty-seven of these lines are not observed in the model, of which 15 are from Bi, U, Pb, Tl and Th contaminates (not modeled) and 7 lines in the HEAO 3 data that were not identified [14]. There are several lines (associated with ^{24}Na and ^{27}Mg) in the model, which disagree with the measured amplitude by a factor of 3 to 4. The ^{69}Ge lines at 573, 872, 1107, and 1337 keV, with additional lines 10 keV higher due to x-ray fluorescence (with a fluorescence yield of 53%), differ from the measured background rate. This also appears to be true for the ^{67}Ga lines. There are no lines in the model that are not also found in the data within the statistics of comparison. Eighty-six lines are observed in the model that agree with lines in the data. Most of the lines not apparent in the model are weak lines, thus may be absent due to limited statistics.

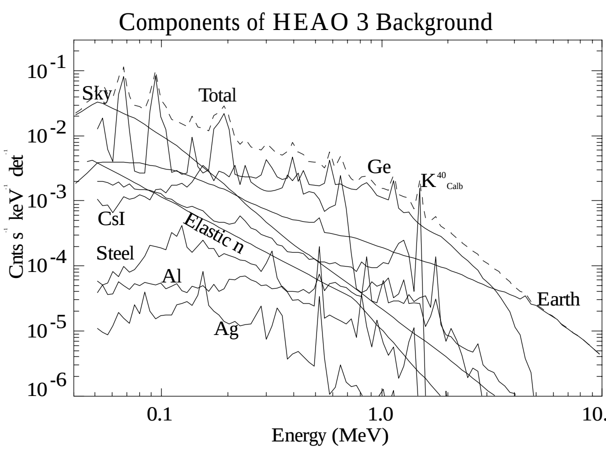

Figure 3 Shows the contribution from each activated component with logarithmic binning blurring some of the lines.

The modeled background rate broken into its constituent components in Figure 3 shows where different portions of the background spectrum are dominated by decays produced in different components of the instrument. At low energies, below 120 keV, the cosmic diffuse sky dominates the background spectrum. From 120 keV to 700 keV decays from the Ge detectors and the CsI shield are dominant. From 700 keV to nearly 4 MeV the activation in the Ge detectors dominates. Above 4 MeV the atmospheric flux from the Earth dominates. The aluminum, steel, and silver contribute to some lines, (e.g. 511 keV) but do not contribute significantly to the continuum due to their small mass and distance to the detectors. Decays of isotopes produced in the CsI contribute significantly to the background due to the large mass of the shields, although most isotopes decaying in the CsI have strong veto efficiency (most are better than 99.9%). The only decays of unstable isotopes produced in the CsI that contribute to the background are isotopes where the energy of the beta particle that occurs is less than the threshold of the shields and a gamma-ray is emitted in the decay that scatters in or is absorbed by the detector.

The HEAO 3 simulation has been used to validate the Monte Carlo Model. The future plans for this model is to apply this model to more complicated instruments such as INTEGRAL and a proposed high resolution Compton telescope.

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